Efficient THz-bandwidth Quantum Memory in Atomic Barium

Kai Shinbrough,[1,2,*] Benjamin D. Hunt,[1,2,3,4] Sehyun Park,[5,6] Kathleen Oolman,[1,2] J. Gary Eden,[5] and Virginia O. Lorenz[1,2]

[1] *Department of Physics, University of Illinois Urbana-Champaign, 1110 W Green St, Urbana, IL 61801, USA*
[2] *IQUIST, University of Illinois Urbana-Champaign, 1101 W Springfield Ave, Urbana, IL 61801, USA*
[3] *Department of Physics, University of Colorado Boulder, 390 UCB, Boulder, CO 80309, USA*
[4] *National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*
[5] *Department of Electrical and Computer Engineering, University of Illinois Urbana-Champaign, 306 N Wright St, Urbana, IL 61801, USA*
[6] *Department of Physics and Astronomy, Rice University, 6100 Main St, Houston, Texas 77005, USA*

[*] *kais@illinois.edu*

Abstract: We report record storage efficiencies in the first atomic THz-bandwidth quantum memory. Near-off-resonant orbital transitions in collisionally broadened hot atomic barium vapor allow for 83% storage efficiency, 25% total efficiency, and a time-bandwidth-product of 800.

Optical quantum memory is a critical resource for many quantum information protocols and technologies. We present an atomic ensemble memory that exhibits record high efficiency and bandwidth, moderate storage time, low noise, frequency-tunability, telecom-compatibility, and low latency. Our quantum memory platform consists of a hot (>800 °C) vapor of netural atomic barium (Ba) in argon (Ar) buffer gas. Collisional broadening of the Ba excited state due to the Ar buffer gas is critical to our scheme, and allows for memory operation in the ultra-broadband regime [THz-bandwidth, O(100 fs) pulse duration].

Each Ba atom possesses a three-level internal Λ-system consisting of the ground ($|g\rangle$) $6s^2\ ^1S_0$ state, excited ($|e\rangle$) $6s6p\ ^1P_1$ orbital state, and metastable $6s5d\ ^1D_2$ orbital storage ($|s\rangle$) state. The $|g\rangle \to |e\rangle$ transition occurs in the visible at 553.5 nm, whereas the $|e\rangle \to |s\rangle$ transition occurs in the telecom S-band at 1500 nm. All atoms initially populate the $|g\rangle$ state and we tune a weak, 500 fs coherent state signal field (with <0.5 photons per pulse on average) and strong, 100 fs control field [O(10 uJ) pulse energy] to approximately 5 excited state linewidths red-detuned from the atomic transitions. This small detuning eliminates linear absorption in the absence of the control field and allows us to measure storage efficiency directly by counting the number of photons arriving at a detector with and without the control field. The control field is derived from an 800 nm optical parametric amplifier with 1 kHz repetition rate and the signal field is generated via sum-frequency generation of the control field and light from an 877 nm laser diode. Both Ar buffer gas and barium vapor are confined inside a home-built heat pipe oven with 12 inch heated region, and the signal and control fields are focused in the center of the oven with waist radii (109±3) μm and (247±4) μm, respectively.

After optimization of our control field frequency, pulse area, delay (relative to the signal field), and beam pointing, we measure experimentally a storage efficiency of (83±1)%. At our optical depth of 15, the theoretical optimal bound on our storage efficiency is $\eta_{\text{opt}} = 86.5\%$ [1], which yields a normalized storage efficiency for our memory of (96±1)%. Compared to existing broadband, on-demand quantum memories, shown in Fig. 1(a), this measurement represents a significant improvement in efficiency in the ultra-broadband regime. We attribute this improvement in efficiency to the large [O(100 GHz)] collisionally broadened excited state linewidth in our system; as shown in previous work, excited state linewidth plays a critical role in determining memory efficiency in both the resonant and near-resonant regimes [2]. Additionally, our memory represents the first atomic THz-bandwidth quantum memory—all previous THz-bandwidth quantum memories have made use of phononic storage states either in molecular gases or solids. In Fig. 1(b), we show that this improvement in memory efficiency and bandwidth has not come at the cost of significantly shorter memory lifetime; our memory follows the trend set by the rest of the broadband memories in the literature.

In addition to measuring memory efficiency, we have begun to probe the coherence of our memory. In Fig. 1(c), we show measurements of storage efficiency as a function of control field pulse area, which exhibit a half Rabi cycle. In Fig. 1(d), we show measurements of our memory lifetime as a function of Ar buffer gas pressure, where quasi-static collisional dephasing limits the storage lifetime at large Ar pressures. Current work is focused on diagnosing the small storage lifetimes at low Ar pressure, which may be due to the formation of Ba-Ar molecules. At an Ar pressure of 150 torr, we find a saturation of the ballistic limit on our storage lifetime, where the lifetime is limited by Doppler dephasing and may be enhanced further with the use of a sensor state [3].

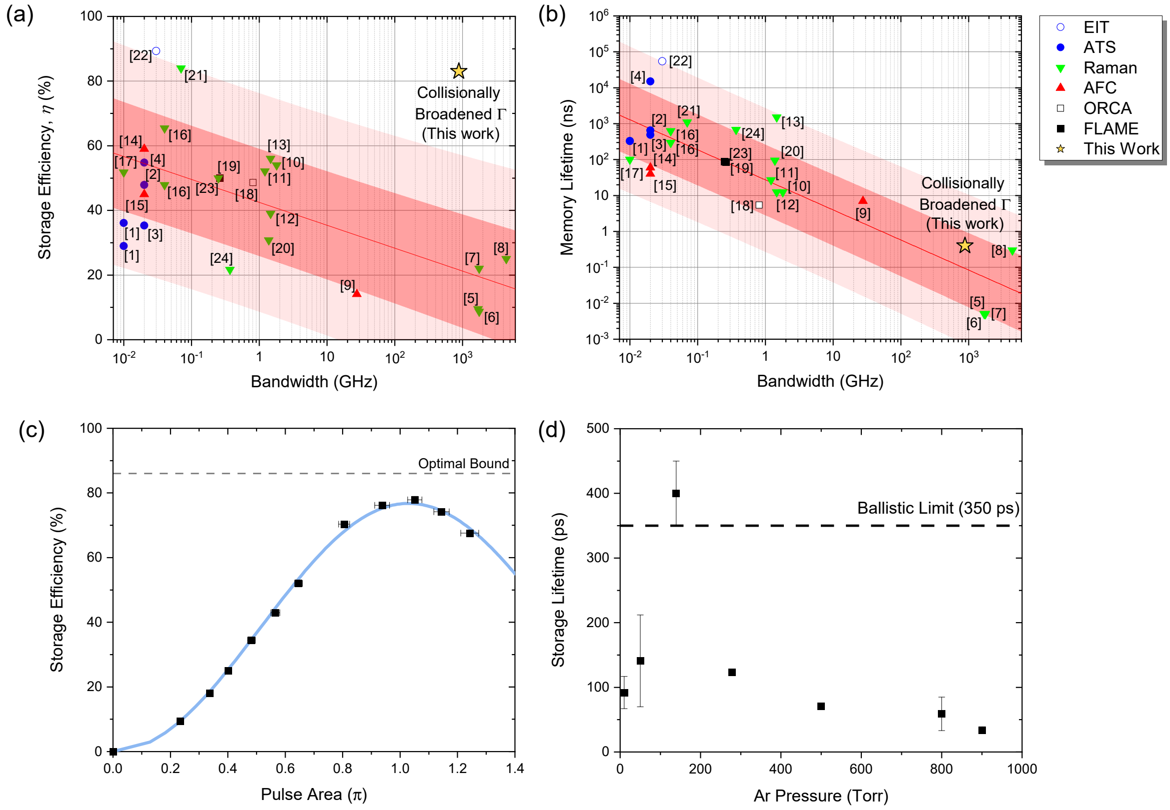

Fig. 1. A review of the broadband, on-demand quantum memory literature (a) normalized storage efficiency and (b) memory lifetime as a function of memory bandwidth. Numbered citations given in Ref. [4]. (c) Storage efficiency versus pulse area for our memory, showing a half Rabi cycle. (d) Memory lifetime versus Ar buffer gas pressure for our memory, showing an optimal buffer gas pressure where memory lifetime saturates the ballistic lifetime limit.

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